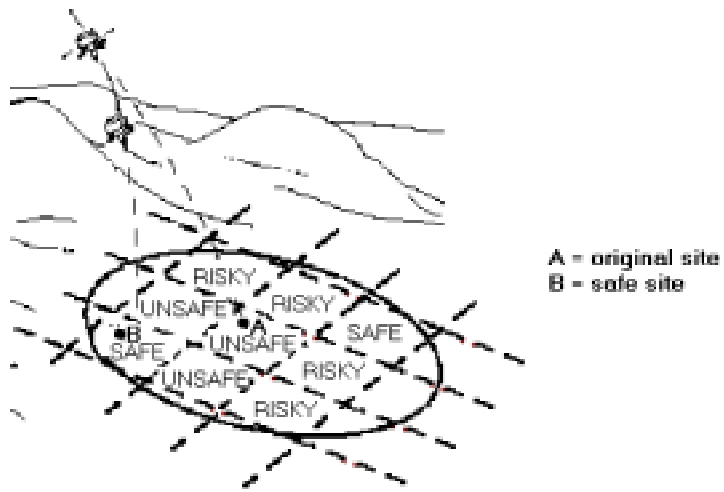
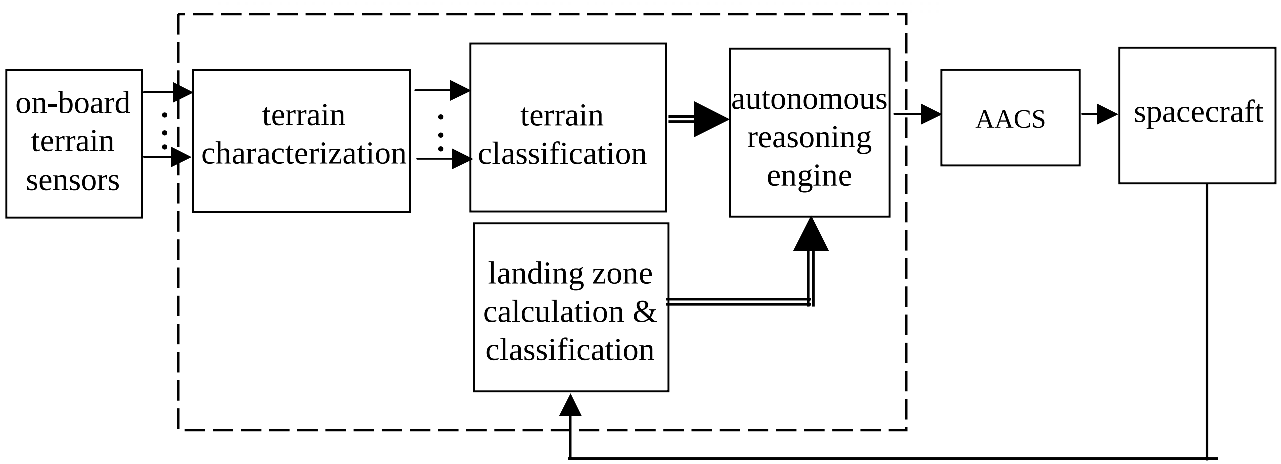
Safe Landing of Robotic Spacecraft

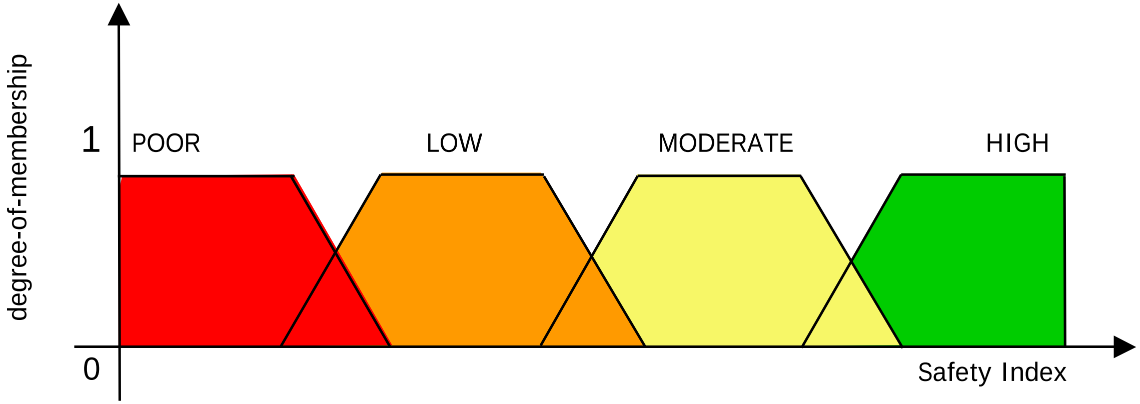




Landing Site Safety Assessment

- Landing site safety is quantified by the **Rule-Based Safety Index,** which is dependent on the sensed terrain characteristics through a set of linguistic conditional statements (rule base).

- The **Safety Index** is represented by the four linguistic classes {POOR, LOW, MODERATE, HIGH} that correspond to landing sites which are {UNSAFE, MODERATELY-UNSAFE, MODERATELY-SAFE, SAFE}, respectively.



Four classifications of terrain safety

Key Attributes of the Approach

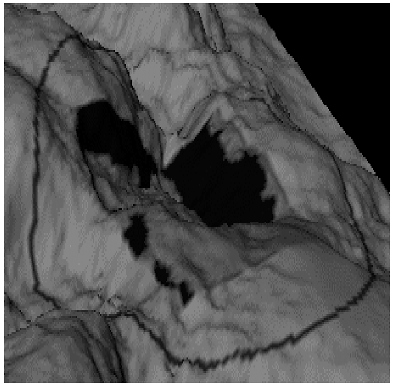
- **Gradual Gradation**: Utilizes multiple grades of safety for landing site evaluation represented by easily-understandable linguistic classes, such as {UNSAFE, MODERATELY-UNSAFE, MODERATELY-SAFE, SAFE}, allowing smooth transitions between different classes.

- **Robustness:** Enjoys high robustness because of its capability of handling sensor imprecision and uncertainty in data interpretation. This is particularly important in EDL because of the jittering and vibrations of the terrain sensors mounted on the spacecraft.

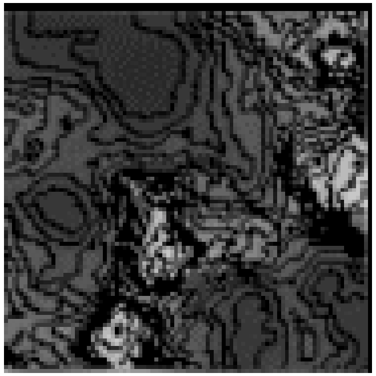
- **Extensibility:** Can easily incorporate several terrain characteristics for landing site evaluation obtained by multiple sensors (e.g., radar reflectivity, albedo, thermal inertia), in addition to roughness and slope. This is achieved easily by adding a set of new rules to the existing rule base.

Computing terrain characteristics

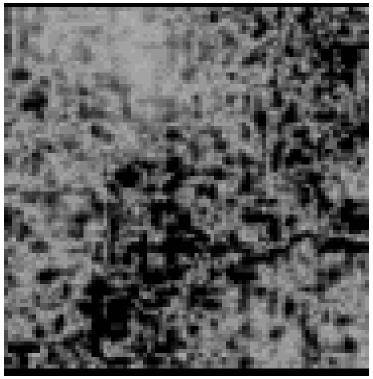
Range data is converted into an elevation map. A least-squares plane fitting algorithm is used to compute slope and roughness.



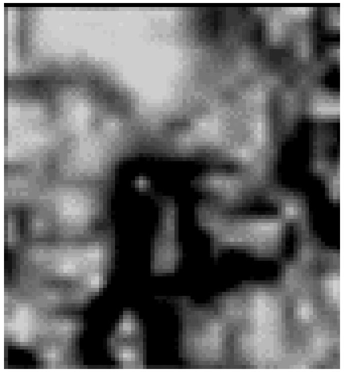
Terrain map



Elevation



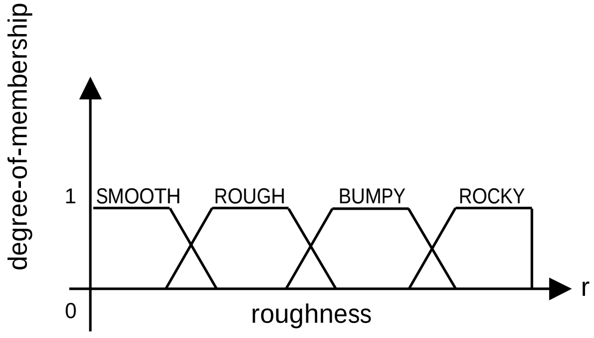
Roughness



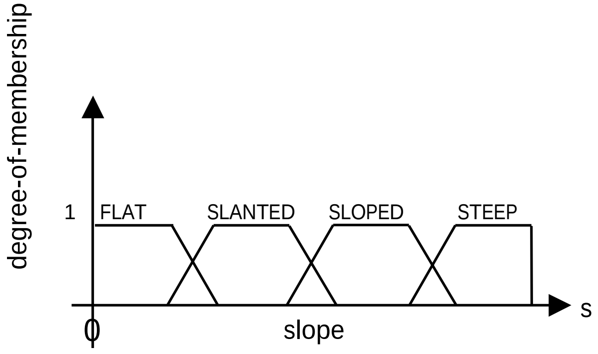
Slope

Representing terrain characteristics

Terrain characteristics are converted into linguistic representation using fuzzy logic sets. Roughness is represented by the linguistic fuzzy set *{SMOOTH*, *ROUGH*, *ROCKY}*. Terrain slope parameter is converted into the linguistic representation *{FLAT*, *SLOPED*, *STEEP}*.



Four classifications of terrain roughness extracted from radar and lidar measurements



Four classifications of terrain slope extracted from radar and lidar measurements

Safety Map Generation using Lidar and Radar

safe site

- IF roughness IS SMOOTH AND slope IS FLAT, THEN terrain_Safety IS HIGH.
- IF roughness IS SMOOTH AND slope IS SLANTED, THEN terrain_Safety IS HIGH.
- IF roughness IS ROUGH AND slope IS FLAT, THEN terrain_Safety IS HIGH.

moderately-safe site

- IF roughness IS SMOOTH AND slope IS SLOPED, THEN terrain_Safety IS MODERATE.
- IF roughness IS ROUGH AND slope IS SLANTED, THEN terrain_Safety IS MODERATE.
- IF roughness IS BUMPY AND slope IS FLAT, THEN terrain_Safety IS MODERATE.

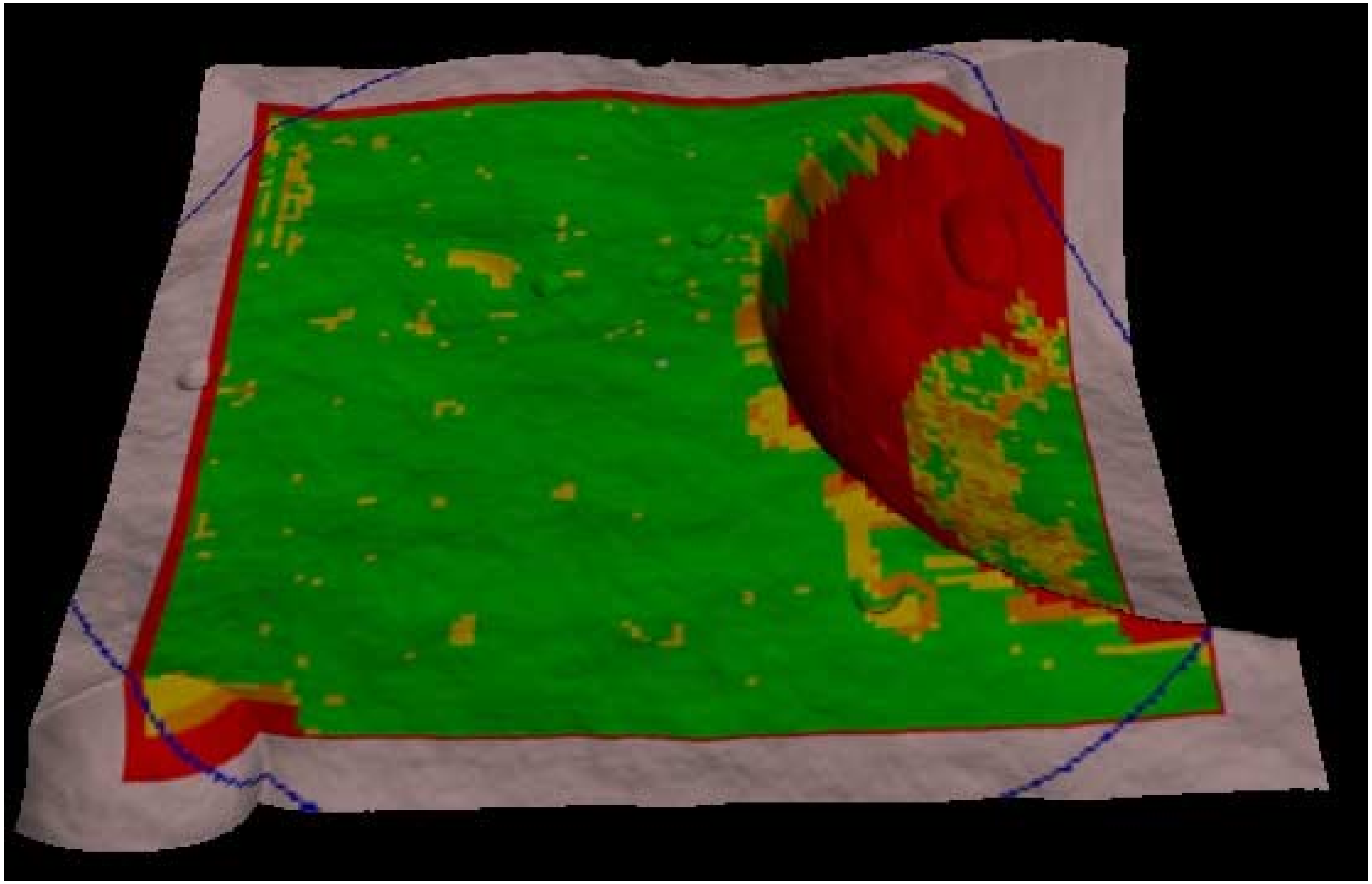
moderately-unsafe site

- IF roughness IS ROUGH AND slope IS SLOPED, THEN terrain_Safety IS LOW.
- IF roughness IS BUMPY AND slope IS SLANTED, THEN terrain_Safety IS LOW.
- IF roughness IS BUMPY AND slope IS SLOPED, THEN terrain_Safety IS LOW.

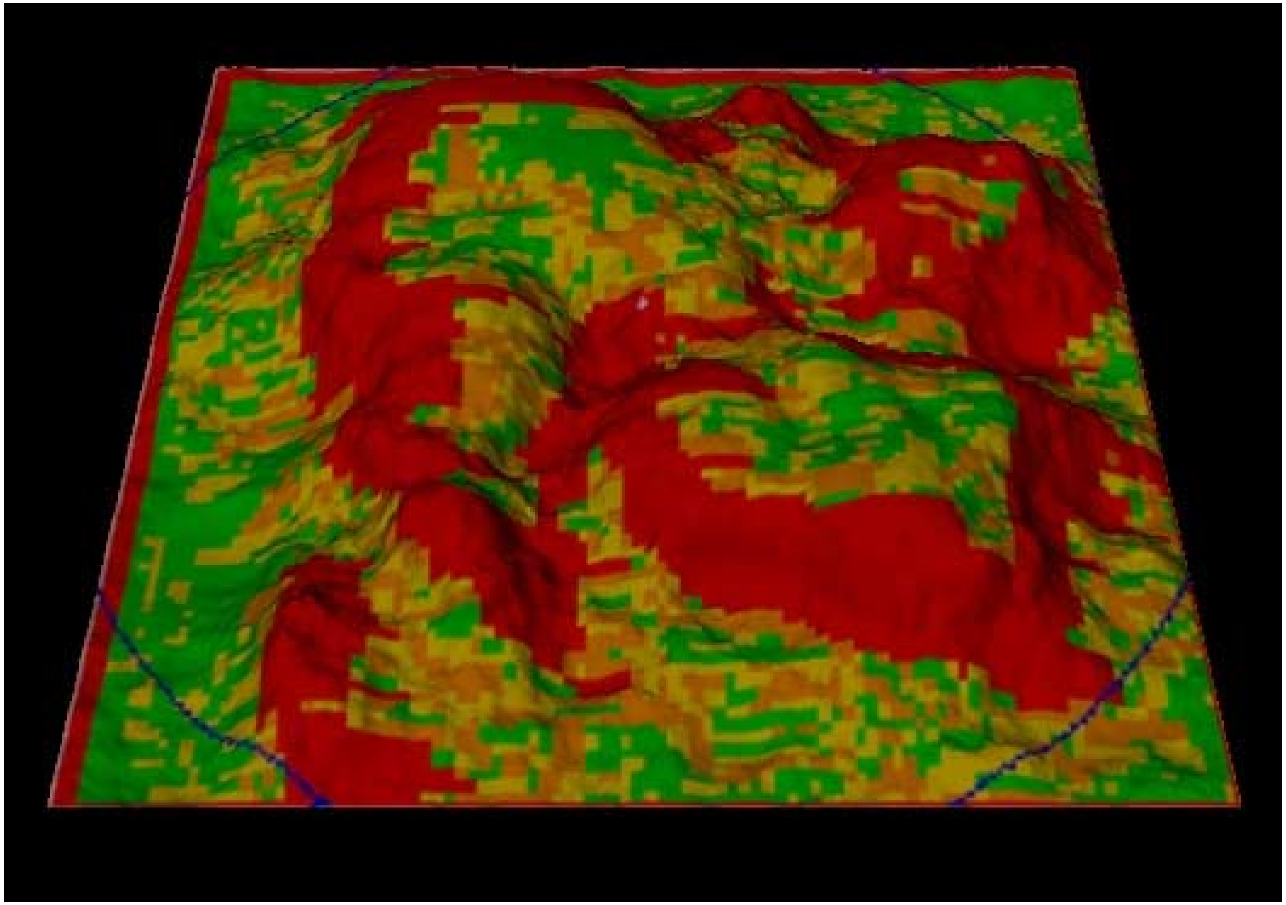
unsafe site

- IF roughness IS ROCKY OR slope IS STEEP, THEN terrain_Safety IS POOR.

Safety Map Computed for a Mars Terrain

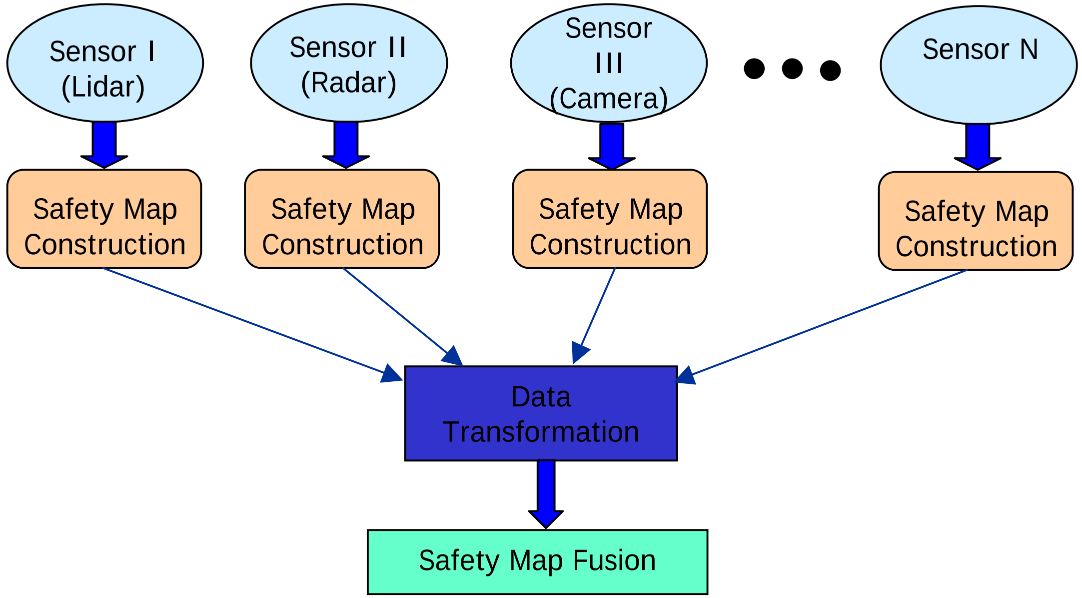


Safety Map Computed for a Comet Surface

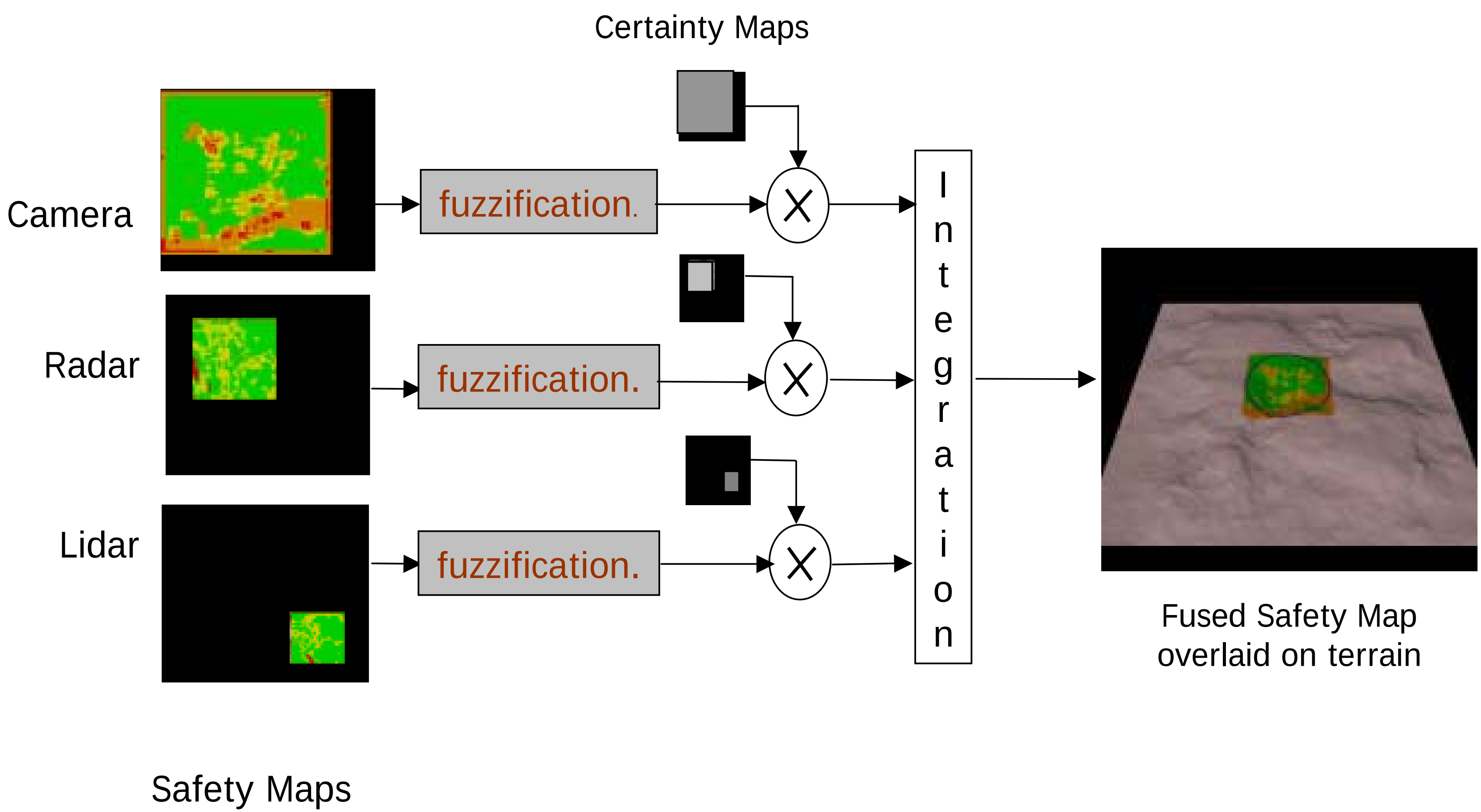


Multi-Sensor Information Fusion

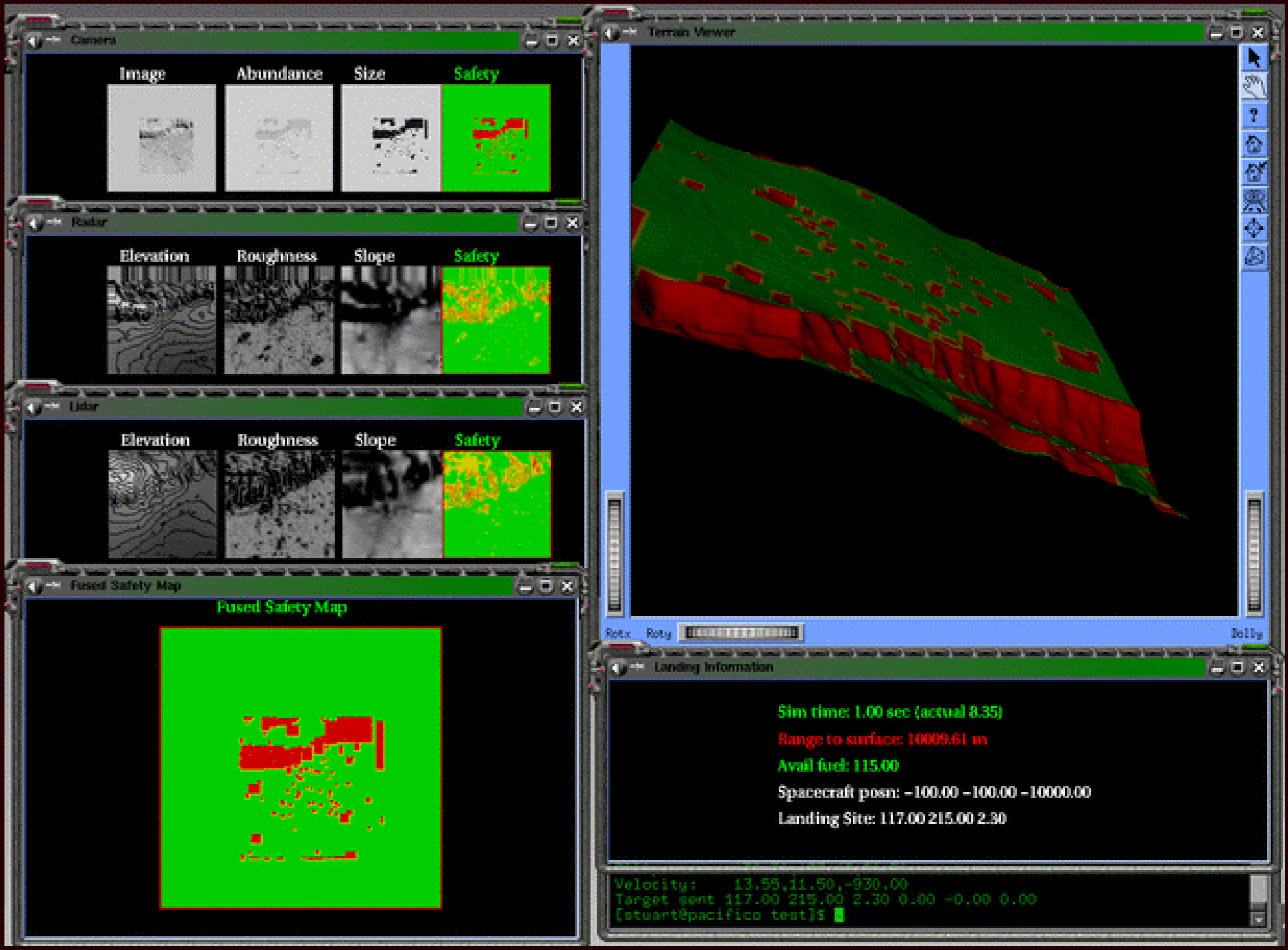
- Combine safety maps derived from each sensor into a global safety map description.
  - Data Transformation
    - to compensate for parameter variations among different sensors
  - Fuzzy Fusion Engine
    - to combine individual safety maps into a fused safety map representation of the terrain



Information Fusion Process



Simulation


Camera
Image
Abundance
Size
Safety
Radar
Elevation
Roughness
Slope
Safety
Lidar
Elevation
Roughness
Slope
Safety
Fused Safety Map
Fused Safety Map
Terrain Viewer
Rotx
Roty
Dolly
Landing Information
Sim time: 1.00 sec (actual 8.35)
Range to surface: 10009.61 m
Avail fuel: 115.00
Spacecraft posn: -100.00 -100.00 -10000.00
Landing Site: 117.00 215.00 2.30
Velocity: 13.55,11.50,-930.00
Target sent 117.00 215.00 2.30 0.00 -0.00 0.00
[stuart@pacifico test]$